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VAR AND ESR: DO THEY MEASURE UP

August 1975

BENET WEAPONS LABORATORY
WATERVLIET ARSENAL
WATERVLIET, N.Y. 12189

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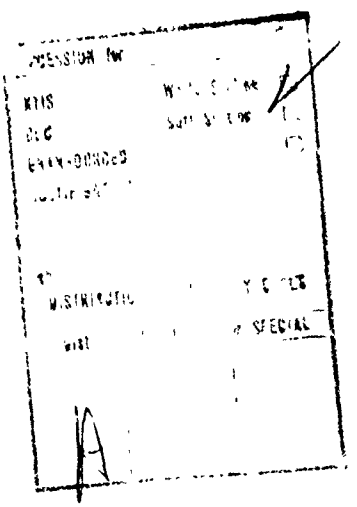
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Large gun tube forgings are presently produced from statically-cast electric arc furnace steel ingots. Vacuum Arc Remelting (VAR) and Electroslag Remelting (ESR) are two secondary refining processes applied to conventionally produced steel. A comparison of VAR and ESR is made with basic electric arc steelmaking, via a review of current literature. These refining processes greatly improve the structure and properties of low alloy steel. Gas and inclusion contents are lowered, and mechanical properties and soundness are improved. VAR is a simpler and more developed process than ESR, but the

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20. latter is more flexible and versatile. In addition ESR produces a much higher yield.

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INTRODUCTION

The steel forgings now being used at the Watervliet Arsenal in the manufacture of cannon tubes are produced by forging static-cast electric-arc furnace melted, modified 4335 steel. However, the mechanical and physical properties required in gun tubes are very demanding. Therefore, we are constantly seeking improved and more efficient methods of production. Vacuum Arc Remelting and Electroslag Remelting are two secondary refining processes applied to conventionally produced steel, which claim improved structural and mechanical properties. Accordingly, an evaluation of these processes was undertaken via a literature search, to compare them with each other and with the presently used process.

DESCRIPTION OF PROCESSES AND EQUIPMENT

The first successful commercial direct-arc steel making furnace was placed in operation by Heroult in 1899, and the first electric-arc furnace was introduced into the U.S. in 1906. Today, gun steel is produced by the basic electric-arc process and vacuum treated either by the D-H process or by stream degassing into an intermediate ladle or into ingot molds.

Consumable electrode melting is a group of secondary refining processes used to produce special quality alloy and stainless steels. Steel which is originally produced by any conventional steelmaking process and cast or forged into an electrode, is remelted under special controlled conditions. Two major secondary processes are Vacuum Arc

Remelting and Electroslag Remelting. Vacuum Arc Remelting (VAR) is the process of melting an electrode under vacuum by passing an electric arc between the electrode and the base of the mold[1] and re-solidifying into an ingot in a cooled mold.

Electroslag Remelting (ESR) is similar to VAR, but the steel is remelted in air by a molten refining slag, resolidifying beneath the slag layer. Both VAR and ESR produce steel ingots of very high quality. Today, VAR is an established and widely used method of producing high quality, large steel ingots throughout the world. ESR has been a production process in the U.S.S.R. for a few years, but is only in the developmental and early production stage here in the U.S.A.

A. Basic Electric Arc Furnace

The Basic Electric Arc Furnace produces steel by passing a 3-phase, a.c. current through the steel scrap charge. The scrap is heated by radiation from the arc, and by resistance heating of the steel itself. A basic refractory lining is used almost exclusively for low alloy steels. The bottom, or subhearth, of the furnace is usually a burned magnesite brick covered by granular magnesite. The sidewalls are a metal-encased magnesite brick, and the roof is generally a high alumina brick. The exterior furnace shell is usually a welded or riveted cylinder of mild or austenitic steel[1]. Figure 1 shows the construction and refractories of the Heroult Furnace.

1. The Making, Shaping and Treating of Steel, ed. by Harold E. McGannon, U.S. Steel, 8th edition, 1964, p. 519

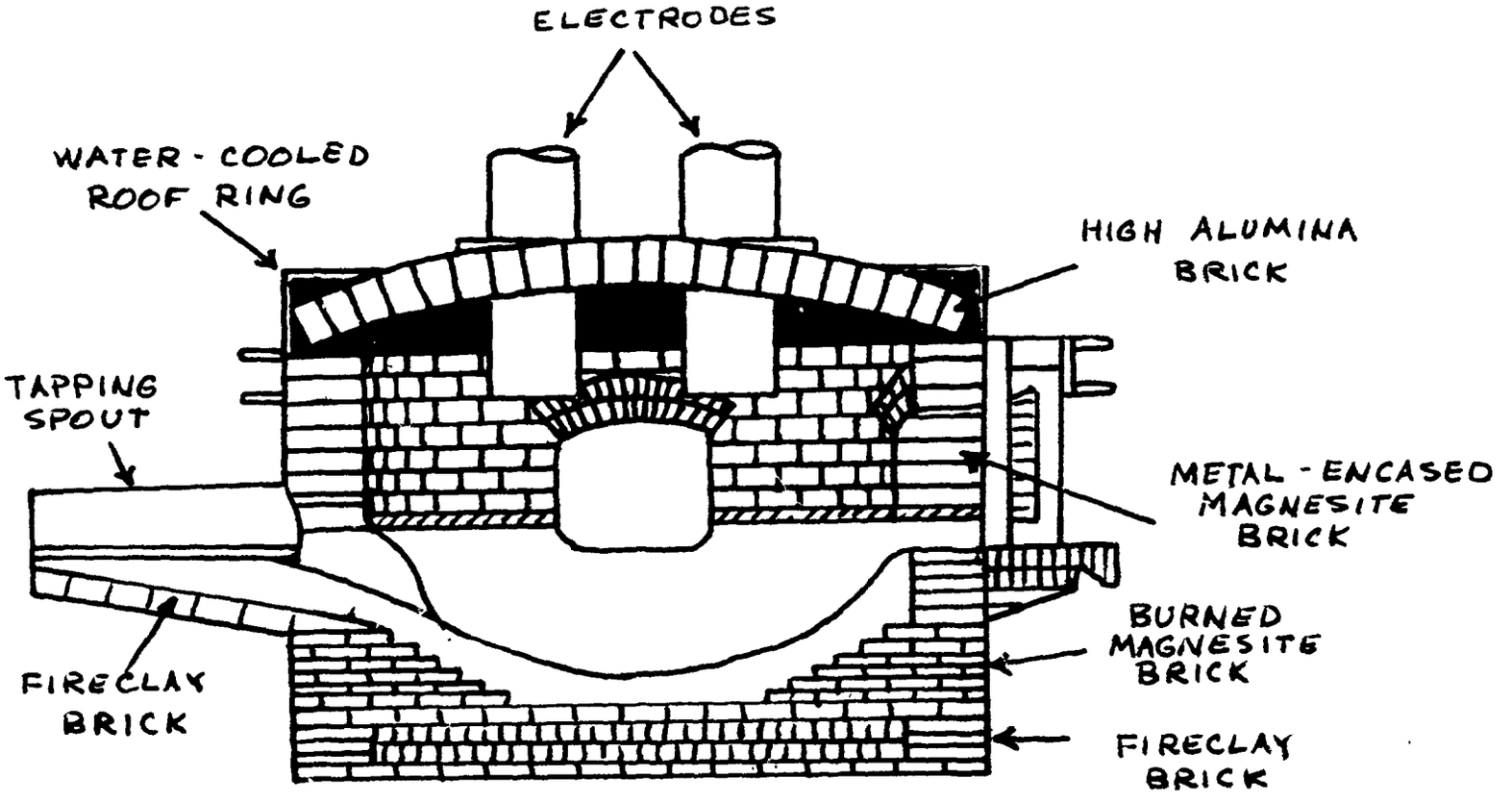


Figure 1. Schematic cross section of Heroult electric arc furnace with flat-bottomed shell and stadium-type subhearth, showing a basic lining. Only two of the electrodes are shown*

*Adapted from Reference (1)

The electrodes are long cylinders of either graphite or carbon, passing through openings in the roof, usually spaced at the corners of an equilateral triangle. Water-cooled rings are placed over the openings and around each electrode to act as a seal. The electrodes are supported by water-cooled clamps extending over the furnace, to which the electrical connection is made. Power is supplied by large transformers, cooled by water or oil[2].

The furnace, which is mounted on toothed rockers resting on toothed rails, can be tilted by motors in two directions, one for pouring, one for slagging. Some furnaces have mechanical or induction stirrers underneath. Most furnaces are top-charged, and are equipped with mechanisms to raise the electrodes and swing the roof away.

The bottom is charged with a thin layer of light scrap; heavy scrap is piled within the delta of the electrodes; and light scrap is piled around the sides to protect the refractories from the arc. After the roof is repositioned, and the electrodes lowered to within an inch of the scrap, the main circuit is closed and an arc is struck at an intermediate voltage. After approximately 15 minutes, maximum voltage and current are applied for fast melting. Throughout the melt, P, Si, Mn, and C are oxidized readily. The production of CO gas gives rise to a boil which agitates the bath[2].

2. The Making Shaping, and Treating of Steel, ed. by Harold E. McGannon, U.S. Steel, 8th edition, 1964, p. 537

After the first (oxidizing) slag is removed by backtilting and raking, the second slag in the double-slag process is produced. The second slag is a reducing slag containing mostly calcium carbide. Carbon and alloying elements can be added to the slag to adjust the composition. When the steel is sufficiently refined, the electrodes are raised and the power is shut off. The furnace is tilted and the steel is poured into a ladle, with the slag serving as an insulating blanket. The steel is then D-H degassed or stream degassed into an intermediate ladle or into the mold in a vacuum chamber at a pressure of less than 200 microns. Figure 2 (a,b) shows two variations of the degassing apparatus.

B. Vacuum Arc Remelting

The Vacuum Arc Remelting (VAR) furnace is simply a water-cooled ingot mold in a vacuum chamber (Figure 3). The mold usually has a copper baseplate which is cooled by a recirculating water system. Cooling systems are designed so that, even in cases of pump failure, water will continue to flow due to gravity, and reduce danger of overheating. The chamber is evacuated through a series of vacuum pumps and filters to a pressure in the range of 5 to 50 microns[3].

To effectively produce nigh quality VAR ingots, the electrode material must be of high quality itself. Electrodes are either vacuum

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3. Dyrkacz, W.W., "Vacuum Melting in the Steel Industry Today", Journal of Metals, Dec. 1957.

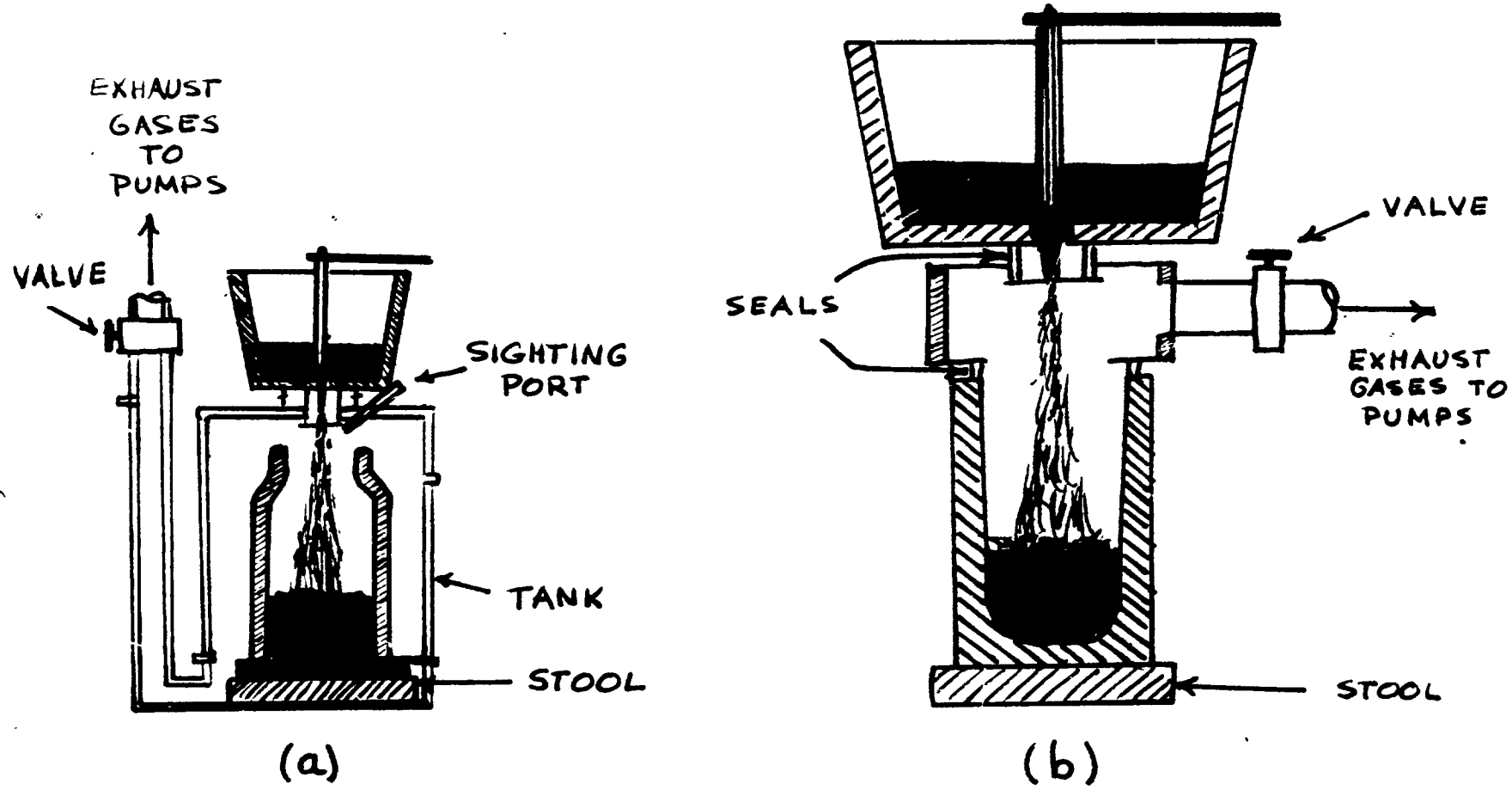


Figure 2. Schematics of two typical ladle to ingot mold vacuum stream degassing processes*

* (a) Adapted from Reference (2)
(b) "Gero Vacuum Casting Process"

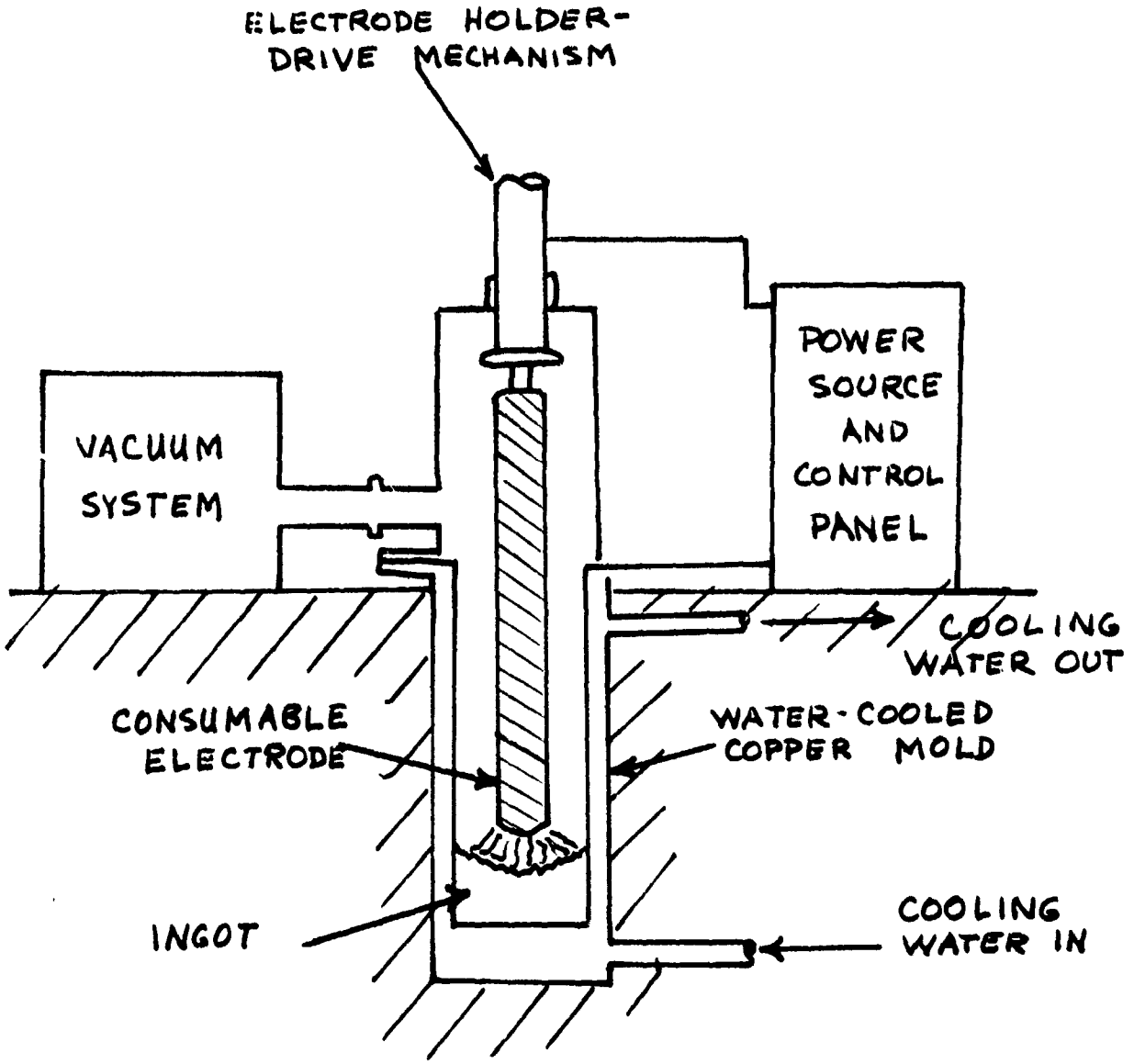


Figure 3. Schematic of Vacuum Arc Remelting (VAR Furnace*

*Adapted from Reference (24)

induction melted and cast to the electrode shape, or conventional ingots forged to shape. Current passes from the electrode to the ingot mold through a low pressure arc. Metal transfers from electrode to ingot as a uniform flow of fine, super heated spray. As the electrode is consumed, it is lowered automatically by a drive mechanism to maintain the arc length and keep it from sparking to the mold wall[4]. Direct current is usually used, with the electrode d.c. negative (cathode).

The chamber is pumped down to the desired pressure, and the leak rate is determined in order to calibrate the pumps for the melt cycle. An arc is struck between the electrode and a small starting block of steel at the base of the mold. Between the electrode and the liquid pool, the metal is subjected to about 5000°K and becomes finely divided through vaporization and degassification. When the droplets reach the liquid pool, they are quenched to 200 to 300°K. The liquid metal pool can be stirred by electromagnetic induction.

The melting rate and the ingot surface quality are affected by the current density[5]. Inclusions, such as nitrides, oxides, and silicates float upward as the melt progresses and some can be found as a scum layer on top of the ingot (Figure 4). The greater is the clearance between the electrode and mold wall, the better will be

---

4. Belk, J.A., Vacuum Techniques in Metallurgy, Pergamon Press, 1963, p. 128.

5. DeFries, R.S., Flynn, E.G., and Dyrkacz, W.W., "Consumable Electrode Remelting of High Temperature Alloys", Allegheny Ludlum Steel Corp., Watervliet, N.Y., Report #11-0160-1, 1955, p. 6.

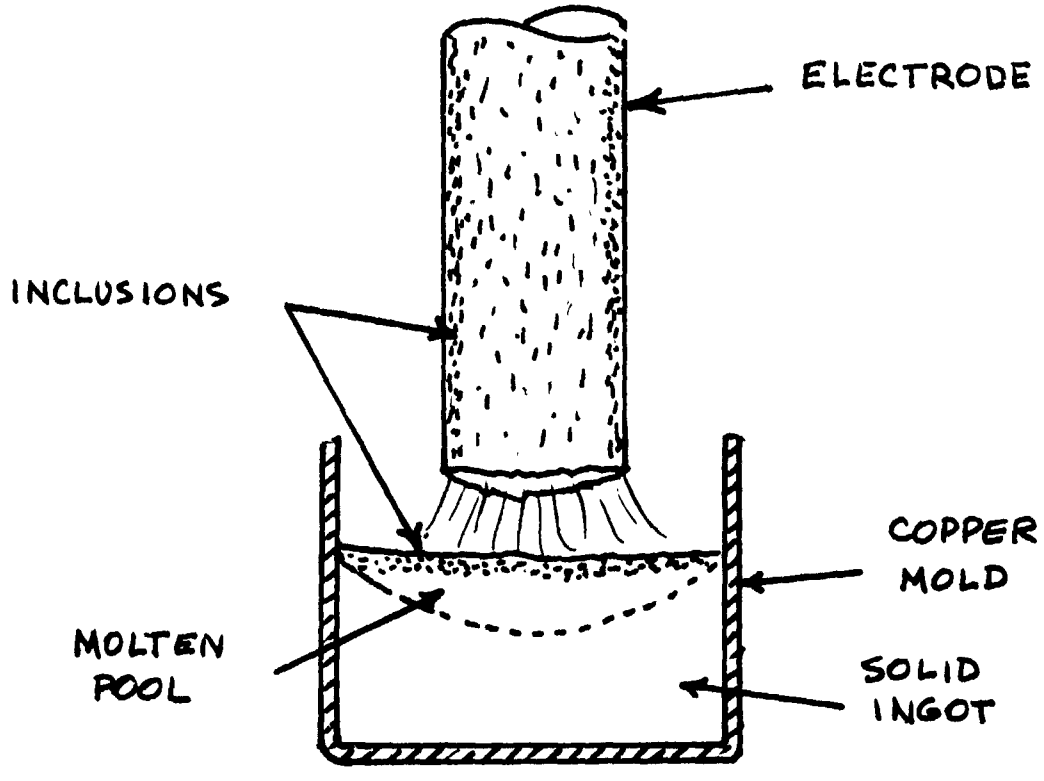


Figure 4. Schematic of VAR electrode tip and top of ingot, showing mechanism of inclusion removal by floatation*

*Adapted from Reference (5)

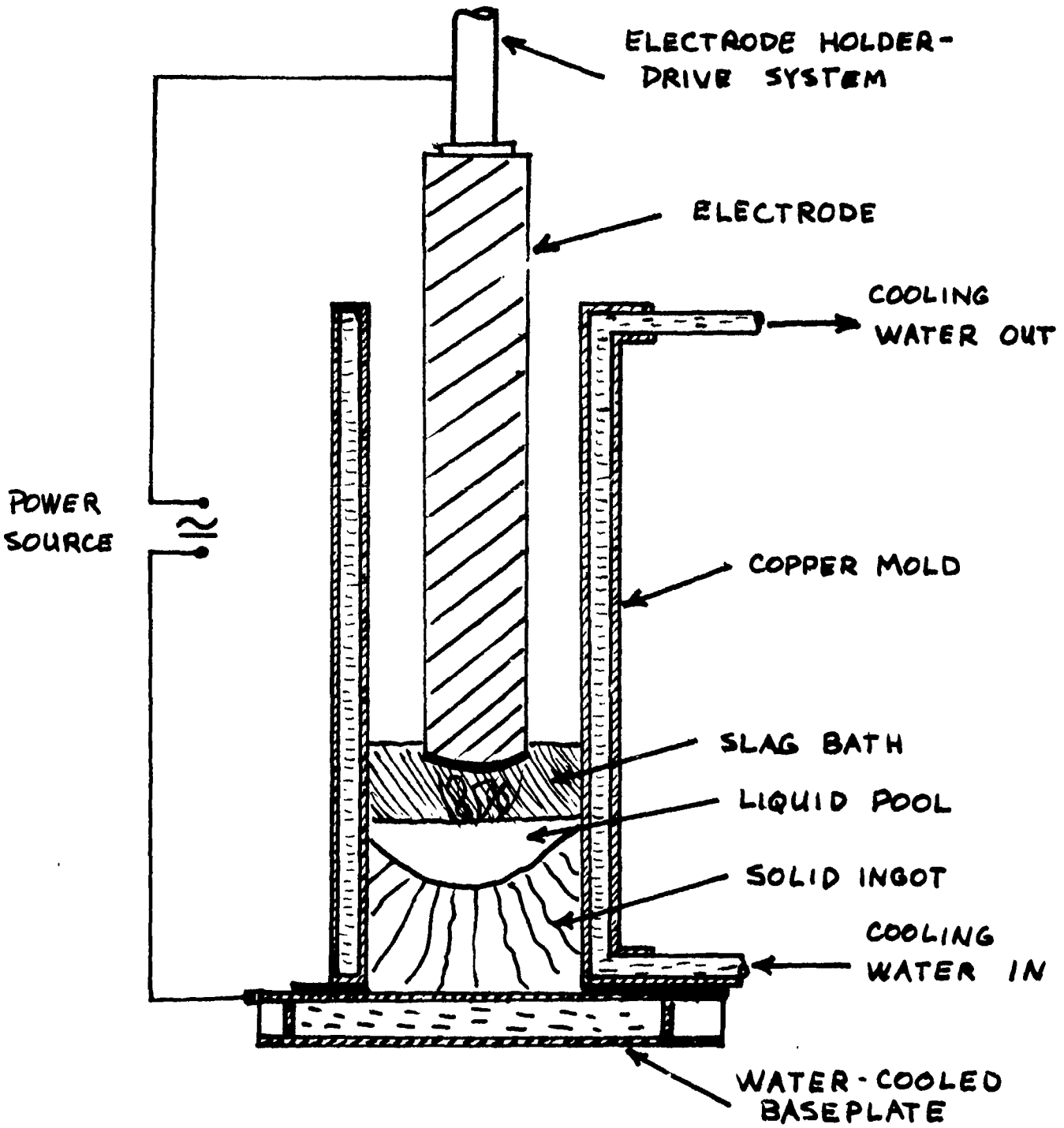


Figure 5. Schematic of Electro-Slag Remelting (ESR) Furnace*

*Adapted from Reference (9)

the removal of impurities. The high temperature in the arc region helps to break down impurities, and the low pressure helps to degas the steel[6].

C. Electroslag Remelting

The Electroslag Remelting (ESR) furnace is constructed similar to the VAR furnace, with a water-cooled copper mold and baseplate. There are no special atmospheric requirements in ESR; the top of the furnace is open to the air. The electrode drive system is similar, and the electrodes are prepared in the same way as in VAR. Figure 5 shows the design of the ESR furnace.

The major difference between ESR and VAR is the use of slag as the heating element and refining bath instead of an arc. Power is transmitted from electrode to baseplate, through the slag bath and the ingot. The resistance of the slag heats the tip of the electrode and melts it. The resultant drops of molten steel are refined as they fall through the slag. The tip of the electrode is immersed in the slag layer which floats on the molten metal pool and excludes the outer atmosphere[7]. The major component of the highly basic slag is calcium fluoride, but it can also contain lime, magnesia, alumina, and silica. The slag must have a low melting point, high stability, low volatility and refining reactivity. The depth and composition of the slag pool must be maintained throughout each melt

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6. Belk, J. A., Vacuum Techniques in Metallurgy, Pergamon Press, 1963, p. 128

7. Carvajal, L. Fernando and Geiger, G.E., Metallurgical Transactions, vol. 2 (1971), p. 2087

to insure uniform properties. Changes in composition will alter the melt rate, slag temperature, droplet size, and other factors affecting the refining rate[8].

The ESR furnace can be operated on either a.c., d.c., straight polarity, or reverse polarity. A.C. is the simplest and lowest in cost, but it cannot be used to melt large ingots. D.C. can melt large ingots, but only with low reliability and high power cost[9]. In the a.c. mode, the furnace can be single phase with 1 electrode and 1 mold, single phase with 2 electrodes and 2 molds, 3 phase with 3 electrodes in 1 mold, or 3 phase with 3 electrodes in 3 molds[8]. The furnace may be started by striking an arc between the electrode and the solid slag (cold start), or by using premelted slag (hot start) in the bottom of the ingot mold[9]. Once the circuit is closed with the tip of the electrode in the slag bath, the electrode melts through the slag into the growing pool of molten steel below. A stirring pattern in the slag bath and metal pool can be superimposed by electromagnetic induction[10].

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8. Duckworth, W.E. and Hoyle, G., Electroslag Refining, 1969, B.I.S.I., p. 11.

9. Schlatter, Rene', "Electroflux Remelting of Tool Steel", Metals Engineering Quarterly, Feb. 1972.

10. Rawson, J.D.W. and Dawson, D.I., "Ingot Casting by Electroslag Remelting", Solidification Technology, ed. by Burke, Flemings, and Gorum, 1972.

During the melt, the slag temperature is in the range of 1700° - 2000°C which is much higher than the steel's melting point[11]. Solidification of the ingot normally forms grains at an angle of approximately 30° to the vertical, but a high degree of control is possible. A fast melting rate gives a deep liquid pool, and subsequently radially oriented grain growth, high surface quality, and little compositional change. A slow melting rate with a shallow pool, promotes compositional changes and axially oriented grains[12]. The slag forms an envelope around the ingot as it is displaced upward. This separates the ingot from the mold wall, and ideally produces ingots with very smooth surfaces, free of defects[11].

Inclusions are removed from the ESR ingot both by solution and by chemical reaction with the slag. Nonmetallics are exposed directly to the slag at the tip of the electrode during melting and dissolve into the slag. Only the smaller inclusions escape. The final inclusion content will be lower as the film of molten metal on the electrode tip is made thinner. Volatile or reactive alloying elements are not lost, but easily oxidizable elements decrease in content during melting[12].

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11. Wahlster, Manfred and Choudhury, Alok, "ESR: An Efficient Way to Make Clean Steel", Metal Progress, April 1969.

12. Duckworth, W.E. and Hoyle, G., Electroslag Refining, 1969, B.I.S.I., p. 14.

COMPARISON OF PROCESSES

Both VAR and ESR are complex and require optimum consumable auxiliary process technology. Because of the available combinations of slag chemistry, more flexible power requirements, and freedom of choice of electrode characteristics, ESR has more process flexibility and versatility, but the many degrees of freedom in ESR bring on control problems. The VAR technique has been under development for a long time, and many control problems have been overcome. ESR is a relatively new process and not so well understood. There is a problem with keeping the influencing factors under constant control and making them reproducible on a production scale. The complexity of the ESR process brings with it the possibility of numerous furnace designs and special applications, but it makes the complete automation of ESR more difficult to achieve than VAR[13].

In VAR, there are two major process characteristics which can be varied; the power, and the metal (electrode). In ESR, there are three major process characteristics; the power, the metal (electrode), and the slag[13]. The control of the slag feed, molten slag depth, and slag temperature and composition present many different control problems. The entire area of slag technology and control has yet to be completely understood[14]. ESR electrodes should be thermally treated to avoid

---

13. Mueller-Aue, Hans J., "Analysis of Operational Data of Vacuum Arc and Electroslag Remelting Plant", Journal of Vacuum Science and Technology, vol. 8, No. 6, 1971

14. Elliott, C.F., et. al., "Electroslag Remelting of Superalloys - Production Melting Experience", Metals Engineering Quarterly, May 1970, p.46.

cracking and clinking, calling for extra material handling and additional furnace capacity. Subsequently, scaled surfaces must be cleaned by wire brushing or other cleaning methods[15].

The nature of ESR introduces flexibility and versatility not found in VAR. The electrode-ingot relationship in ESR is not as critical as in VAR. Many shapes can be produced by ESR; e.g., conventional round ingots, slabs, extrusion billet shapes, and simple shape castings. Because the heat is produced in the slag (as opposed to the arc in VAR), multiple electrode configurations can be used without power or electrical problems. Composite electrodes can be used, and within limits, out-of-specification electrodes can be corrected and used by proper flux chemistry[16]. ESR offers significantly higher melting rates than VAR for the same quality steel. In ESR, the molten slag blanket on the top of the ingot acts as a heat source and insulator after power turnoff, simplifying the power turn-down cycle required in VAR to achieve acceptable top solidification and good yield[17].

A few of the recently investigated ESR techniques, are: 1.) Continuous casting and withdrawal of ingot (impossible in VAR because of vacuum requirements), 2.) Casting of hollow tubular ingots by use of a chilled copper mandrel forcing itself through the mushy

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15. Schlatter, Rene', "Electroflux Remelting of Tool Steel", Metals Engineering Quarterly, Feb. 1972.

16. Duckworth, W.E. and Hoyle, G., Electroslag Refining, 1969, B.I.S.I., p. 8.

17. Elliott, C.F., et. al., "Electroslag Remelting of Superalloys-Production Melting Experience", Metals Engineering Quarterly, May 1970, p. 48.

zone beneath the liquid metal pool; 3.) Casting of composite ingots allowed by changing of electrodes; 4.) Modular furnace systems with interchangeable molds and baseplates, to allow easy replacement and process variety; 5.) Molten bottom-slag starting[18].

COMPARISON OF INGOTS: PHYSICAL & MECHANICAL PROPERTIES

Both VAR and ESR are secondary refining processes applied to a conventionally melted and cast steel. The high cost of these secondary processes are in some cases outweighed by the improvement in physical and mechanical properties. Qualitatively, some of these improved properties are[19]:

1. Decreased gas content
2. Improved cleanliness
3. Improved hot and cold work workability
4. Higher Mechanical Properties:
   a. Fatigue strength
   b. Impact strength
   c. Tensile ductility
   d. Hardness uniformity
   e. Creep-rupture
   f. Transverse properties
5. Improved magnetic properties
6. Improved soundness and uniform composition
7. Consistent product - heat to heat and day to day.

A. Gas Content

Gases absorbed by liquid steel from the atmosphere and from process materials can cause undesirable or even harmful properties in

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18. Bhat, G.K., "A Critical Evaluation of the Electroslag Process and its Growth in the USA; Commercial Opportunities and Applications", Industrial Heating, Jan. 1970, vol. 37, No. 1, p. 88.

19. Dyrkacz, W.W., "Properties and Applications of Consumable Electrode Vacuum Melted Steels and Superalloys in the United States", 1960, Allegheny Ludlum Corp., Watervliet, N.Y.

the solid ingot. Flaking, embrittlement, voids and inclusions are some of the effects observed. Even when precautions are taken in the refining and pouring of air-melted air-poured steel, the ingots have to be subjected to long and complicated heating and cooling cycles to promote the diffusion of absorbed hydrogen. Oxygen and nitrogen in the steel combine with impurities and alloying elements to form oxides, cyanonitrides, or nitrides that remain as inclusions[20].

Vacuum-stream degassing of air-melted steel removes a large proportion of gases in the ingots, but VAR is the most effective for the removal of gases. Trapped gases and vaporized nonmetallic inclusions are drawn off by the vacuum. The resulting remelted ingot shows a considerable decrease in content of H_2, O_2 and N_2.

ESR is also very effective in removing gases, but oxygen and hydrogen removal is not so effective as in VAR. Hydrogen can be picked up from hydrated oxides in the slag, cooling water and electrode material. Provided the ingot is not too large, H_2 diffuses on cooling; but in large ingots, H_2 retention is significant. A controlled atmosphere may be required in ESR to reduce H_2 content. A satisfactory reduction in total O_2 content usually takes place, but the low VAR values are seldom reached[21,22].

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20. The Making, Shaping and Treating of Steel, ed. by Harold E. McGannon, U.S Steel, 8th edition, 1964, p. 537.

21. Schlatter, Rene', "Electroflux Remelting of Tool Steel", Metals Engineering Quarterly, Feb. 1972.

22. Peover, M.E., "Electroslag Remelting: A Review of Electrical and Electrochemical Aspects", Journal of Inst. of Metals, 1972, vol. 100, p. 97.

B. Cleanliness

All steel ingots contain nonmetallic inclusions, derived chiefly from the refining (oxidizing and deoxidizing) processes and from erosion of the refractories[23]. The only ready method of lowering inclusion content in air melt steel is careful control of the refining process. Typically low alloy steel ingots contain primarily sulphide and oxide (e.g. MnS, SiO_2, Al_2O_3, etc.) nonmetallic inclusions. Table I compares the cleanliness of 4340 steel produced by air melting, VAR and ESR.

VAR greatly improves the cleanliness of large steel ingots. Nonmetallic inclusions are removed by levitation of stable compounds that collect on the liquid pool surface, and dissociation of unstable oxides or compounds under high temperature and pressure[24] (Figure 4). A comparison of several VAR and air melt heats of 4340 steel was made where inclusions down to 1/64 inch were counted. In every case, the VAR steel was 5 to 10 times cleaner. Inclusions in VAR steel are usually confined to a few, very small, well dispersed sulphides and/or round oxides, with only rare occurrences of stringer oxides and silicates[25].

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23. Johnston, James H., "Consumable Electrode Arc Melting of Non-Refractory Metals", Vacuum Metallurgy, ed. by Rointan F. Bunshah, Reinhold, 1958, p. 159.

24. Dyrakacz, W.W., DeFries, R.S., and Pitler, R.K., "Vacuum Remelting of Superalloys and Steels by the Consumable Electrode Process", Arcs in Inert Atmospheres and Vacuum, ed. by W.E. Kuhn, 1956, p. 107.

25. Republic Alloy Steels, Republic Steel Corp., 1963, p. 373-374.

TABLE I

CLEANLINESS COMPARISON OF AIR-MELT,
VAR AND ESR 4340 STEEL.
(Relative Gradings)*

	Sulfides	Silicates	Oxides	Nitrides
Air-melt	3	2	5	3.5
VAR	1.5	0	1	0
ESR	1	0	0	0

*Adapted from References (24), (25)

ESR also greatly improves the cleanliness of steel. As inclusions in the ESR electrode are exposed to the slag in melting, they dissolve into the slag (Figure 6). Macrocleanliness and freedom from ingot defects are excellent in ESR, but microcleanliness, although generally good, does not meet VAR standards[26]. The workability of both ESR and VAR is improved by lowering the inclusion count. Very rarely do cracks form from the forging of stringer inclusions.

C. Mechanical Properties

The improvements in mechanical properties of ESR and VAR over air melt steel are due primarily to: 1) the increased chemical homogeneity of the material, 2) reductions in gas content and 3) reduction in inclusion content[27]. Property improvements are greatest in the transverse (perpendicular to the solidification) direction, due to the slow, continuous, vertical freezing of the ingots. Slight improvements in the chemical homogeneity of ESR over VAR ingots are caused by the slower melt rate possible in ESR.

Table II gives a comparison of some transverse mechanical properties between ESR, VAR, and air melted steel. Data was collected from heats and ingots of similar sizes and heat treatment. At a given tempering temperature, there is a slight increase in tensile strength of VAR over air melt, and only slight increase in ESR over VAR. However, remelting improves the ductility of steel over air melting, at

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26. Schlatter, Rene', "Electroflux Remelting of Tool Steel", Metals Engineering Quarterly, Feb. 1972.

27. "A Summary of Comparative Properties of Air-melted and Vacuum-melted Steels and Superalloys", DMIC Report 129, March 28, 1960, p.1.

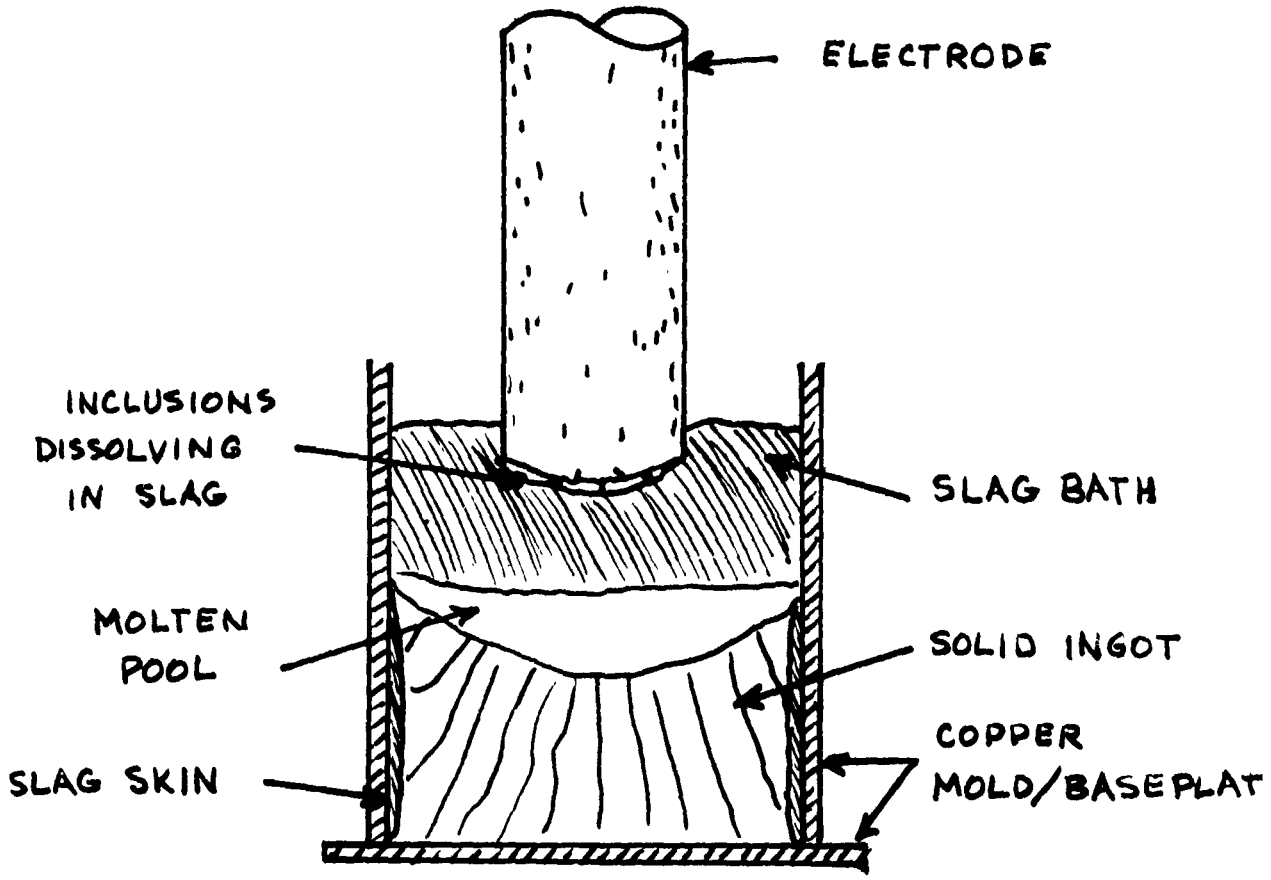


Figure 6. Schematic of ESR electrode tip and top of ingot, showing slag skin, and mechanism of inclusion removal*

*Adapted from References (8),(9)

TABLE II

COMPARISON OF THE TRANSVERSE

MECHANICAL PROPERTIES OF AIR-MELT,

VAR and ESR, 4340 STEEL. (a), (b), (c)

	Air-melt	VAR	ESR
Ultimate Tensile Strength psi	180,000	180,000	189,500
0.2% Offset Yield Strength psi	160,000	160,000	173,000
Percent Elongation	10	10.5	15.7
Percent Reduction in Area	22	24	47.4
Impact Strength ft-lbs (at -40°F)	11.5	17	19.2

(a) Tempered at 1000°F

(b) These data represent averages of several heats

(c) Adapted from References (25), (27)

a constant yield strength level[28], with the %RA of ESR being double that of VAR, for the materials tested. Thus, it is possible that remelting will allow the use of higher strength levels more safely.

The most notable feature of Table II is that each of the ESR properties is improved, but not at the expense of another. In particular, both ductility and impact strength are improved, while yield strength increased. The improved impact strength of both VAR and ESR over air melted steel, is due in part to increased chemical homogeneity and smaller grain size of remelted steels. Improvements in fatigue resistance of remelted over air melted steel have been related to macrocleanliness. The transverse fatigue life of VAR 4340 has been found to be 38% higher than that of air melt 4340 (no data are available for ESR steel)[29].

D. Soundness and Composition

An ideal ingot would be one that was homogeneous both physically and chemically. It would have a fine, equiaxed crystal structure, and no segregation, inclusions or cavities. Unfortunately, the natural laws of solidification produce ingots far from ideal. The cooling rate of an ingot (rate of solidification) is affected by many factors; thickness, shape and temperature of the mold, amount of superheat of the

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28. Morelli, R.T. "Vacuum-Arc-Remelted Steels", Machine Design, Oct. 28, 1971, p. 27.

29. Republic Alloy Steels, Republic Steel Corp., 1968, p. 373-374.

liquid steel, cross-section of the ingot, type of steel, and chemical composition[30].

Figure 7 shows the solidification patterns of a typical static-cast ingot. As the liquid steel cools, the solubility of dissolved gases decreases and the excess gases are expelled from the metal at the surface, or trapped at metal-liquid interfaces, producing blow holes. If blow holes become oxidized, they will not weld in forging, and seams in the rolled or forged product will be the result. The shrinkage cavity at the top of the ingot is called a pipe. It is usually cropped off prior to forging.

The metal that solidifies first at the mold wall is usually the same composition as that entering the mold. The progressive solidification causes the solute (alloys) to be redistributed. Segregation results, and dendrites grow perpendicular to and radially inward from the surface, producing a columnar structure. In the center region of the ingot, an equiaxed zone results[31].

The progressive solidification of a consumable electrode remelted ingot results in a sounder structure than does conventional static casting[32]. Remelted ingots freeze progressively from the

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30. The Making, Shaping, and Treating of Steel, ed. by Harold E. McGannon, U.S. Steel, 8th edition, 1964, p. 548, 549.

31. Chalmers, Bruce, Principles of Solidification, John Wiley and Sons, 1964.

32. Schlatter, Rene', "Electroflux Remelting of Tool Steel, Metals Engineering Quarterly, Feb. 1972.

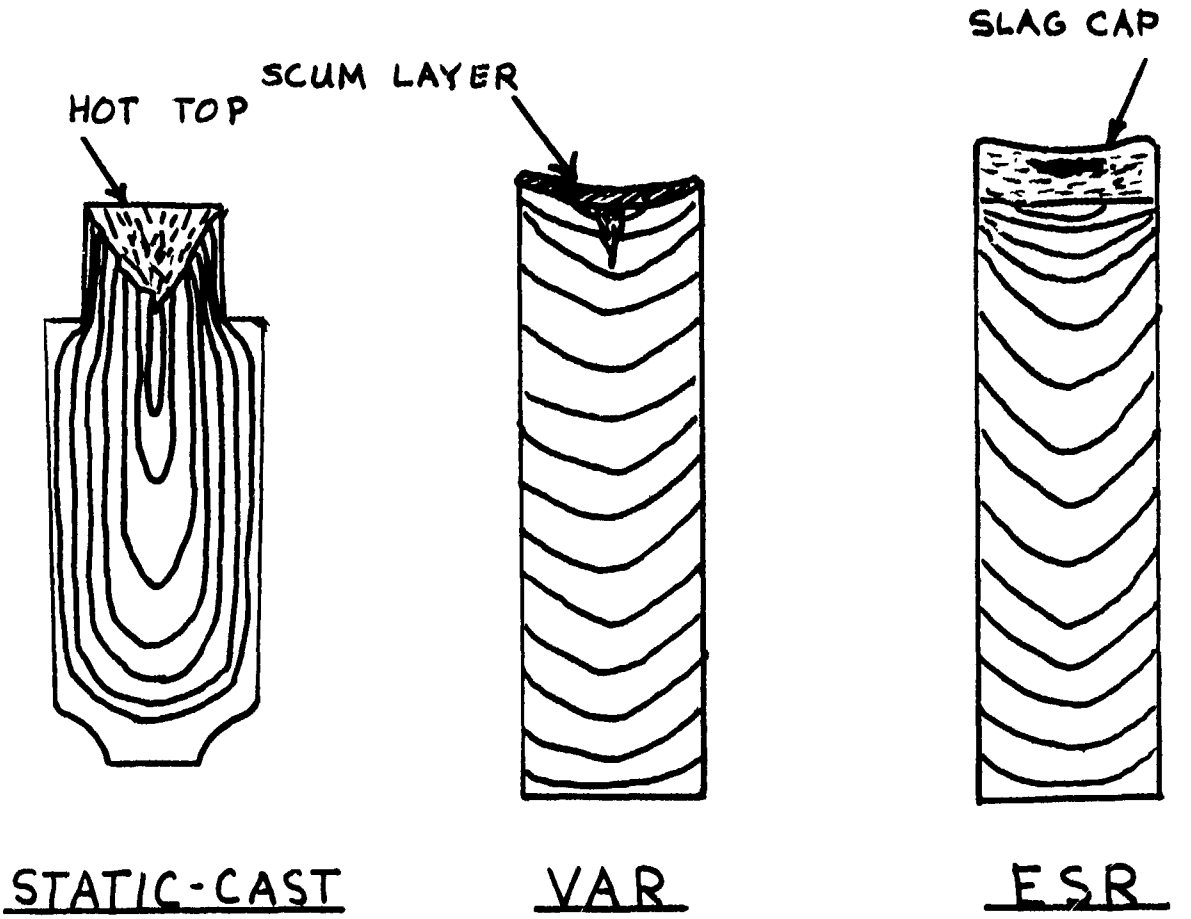


Figure 7. Position of solidification isotherms in static-cast and consumably remelted ingots*

*Adapted from Reference (9)

bottom up, at a much faster rate than conventional, producing a dendrite structure aligned at an angle to the longitudinal axis. A finer dendritic structure results, and secondary dendrite arms may not even be formed. The same principal solidification pattern experienced in VAR is also seen in ESR. Because of the hot slag cap at the top of an ESR ingot, pipe and center porosity are less pronounced than in the VAR ingot (Figure 7)[33].

In both VAR and ESR, the alignment of the grains can be varied from axial to columnar by changing the power pattern and pool depth. Induction stirring, in both processes, improves grain alignment by adding a toroidal component to the structure. Conditions for axial growth are much more favorable in ESR than in VAR. Due to the thermal insulating qualities of the solid slag envelope around the ingot, the proportion of heat lost to the mold wall is very low in relation to that passing through the ingot base. This slag skin envelope also provides an insulating layer which reduces the surface cold-shuts sometimes found in VAR melting. ESR consistently yields smoother and cleaner surfaces than VAR. The molten ESR slag cap acts as a heat source and insulator after power turn-off, simplifying the complicated power turn down cycle required in VAR to achieve acceptable hot-topping. Due to its simplicity, consistently good top yield can be obtained more easily in ESR than in VAR[34].

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33. Rawson, J.D.W. and Dawson, D.I., "Ingot Casting by Electroslag Remelting", Solidification Technology, ed. by Burke, Flemings, and Gorum, 1972.

34. Elliott, C.F., et al., "Electroslag Remelting of Superalloys - Production Melting Experience", Metals Engineering Quarterly, May 1970, p.46.

ECONOMIC CONSIDERATIONS

For all practical purposes, the cost of ESR/VAR electrode feed stock is the same as for a forging ingot from a conventional air melt. The present cost for forged ingots for gun tubes is in excess of $1.00/lb. The cost for equivalent unforged VAR and ESR material is, respectively 57.4 cents/lb. and 50.0 cents/lb.[35]. ESR, therefore, offers the distinct possibility that costs will be reduced and quality improved at the same time.

Due to the variety of furnace designs, and power and melting procedures in use today, valid cost comparisons are difficult to make. Modern ESR equipment has a slightly lower capital cost than VAR, but this is practically outweighed by higher operating cost due to poor power efficiency and significant slag costs. For most steels, ESR permits significantly higher melt rates than VAR to produce the same quality product. Experience has shown that there is very little remelting cost difference between the processes[36].

ESR is competitive with VAR only if it allows higher productivity or shows a marked upgrading of the quality of a specific steel. Higher yield is attained in ESR by improved surface quality, less hot-top and pipe losses, and improved hot-workability[37]. Higher

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35. Duckworth, W.E. and Hoyle, G., Electroslag Refining, 1969, B.I.S.I., p. 162.

36. Schlatter, Rene', "Electroflux Remelting of Tool Steel", Metals Engineering Quarterly, Feb. 1972.

37. Elliott, C.F., et. al. "Electroslag Remelting of Superalloys - Production Melting Experience", Metals Engineering Quarterly, May 1970, p. 47.

melting rates and shorter furnace down time are responsible for increased annual capacity of some ESR furnaces, as high as 30%, over VAR[38]. In air melted, static cast steel, there is a metal loss of approximately 30% from ingot to forged state, made up of 15% top discard, 5% bottom discard, and 10% tolerance over machined component. Good quality ESR ingots can reduce this tolerance to 2-1/2% and can almost eliminate bottom and top discard[39].

Table III shows the annual operating costs of twin VAR and ESR furnaces of the same size. The total operating cost of the ESR furnace was about 25% higher than the VAR, but because of higher yield, ESR steel cost less per unit weight.

SUMMARY AND CONCLUSIONS

Despite the added processing and cost of consumable electrode remelting (VAR and ESR), the resulting refined steel is obviously better than static cast air melted steel. The mechanical properties of VAR steel are slightly better than air melted, but ESR steel has shown higher properties than either. Both VAR and ESR show improved physical properties and chemistry over air melted steel.

Vacuum Arc Remelting (VAR) has been in production for over a decade, but Electroslag Remelting (ESR) is still in the advanced developmental stage. ESR is a much more complex process than VAR,

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38. "The Big Stir in Electroslag Remelting", Iron Age, June 27, 1968, p. 63.

39. Duckworth, W.E. and Hoyle, G. Electroslag Refining, 1969, B.I.S.I., p. 169.

TABLE III

ANNUAL OPERATING COSTS VAR AND ESR -
TWIN 24" FURNACE INSTALLATION*

	VAR $	ESR $
1. Direct labor cost: two men, 15 shifts	48,000	48,000
2. Manufacturing overhead: U.S. average two furnaces	67,000	67,000
3. Melting Power Cost		
(a) VAR 0.3 - 0.4 KWH/lb	23,500	
(b) ESR 0.4 - 0.6 KWH/lb		42,500
4. Cooling water cost with recirculating water system	3,500	4,100
5. Depreciation 10-year straight line based on installed capital cost of		
2 VAR 24" furnace....$480,000	48,000	
2 ESR 24" furnace....$384,000		38,400
6. Depreciation 20-year straight line on building and services, assuming 1000 sq. ft/furnace at $25/sq. ft. Capital cost $50,000	2,500	2,500
7. Slag Cost at 0.4 c/lb of metal melted, assuming molten slag start		28,000
Total Annual Operating Cost	$192,500	$230,500
Total Annual Production	5,600,000 lb	7,000,000 lb
Total Cost	3.4 c/lb	3.3 c/lb

* Adapted from reference (39)

but is also more flexible and versatile. An example of the versatility is the potential of ESR to cast in almost any shape or size (particularly hollow tubular ingots for gun tubes). ESR ingots are more homogeneous and have more isotropic properties than VAR, and can yield a higher tonnage. This increased yield offsets the higher total cost of ESR. The resulting costs/unit weight of VAR and ESR are almost equivalent. VAR results in better gas removal than ESR, especially of hydrogen. Large ESR ingots tend to clink and crack due to hydrogen pickup, unless thermally treated in some way.

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